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LIFE CYCLE MANAGEMENT

Modelling the economic and environmental performance of engineering products: a materials selection case study

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Abstract
Purpose Life cycle assessment (LCA) studies allow understanding all relevant processes and environmental impacts involved in the life cycle of products. However, in order to fully assess their sustainability, these studies should be complemented by economic (LCC) and societal analyses. In this context, the present work aims at assessing all costs (internal and external) and the environmental performance associated to the full life cycle of specific engineering products. These products are lighting columns for roadway illumination made with three different materials: a glass fibre reinforced polymer composite, steel and aluminium.
Methods The LCA/LCC integrated methodology used was based in a "cradle-to-grave" assessment which considers the raw materials production, manufacture, on-site installation, use and maintenance, dismantlement and end-of-life (EoL) of the lighting columns. The *fossil fuels* environmental impact category was selected as the key environmental impact indicator to perform the integrated environmental and cost analysis.
Results The potential total costs obtained for the full life cycle of the lighting columns demonstrated that the one made in steel performs globally worse than those made in composite or aluminium. Although the three systems present very similar internal costs, the steel column has higher external costs in the use phase that contribute for its higher total cost. This column has very high costs associated to safety features, since it constitutes a significant risk to the life of individuals. The raw material and column production stages are the main contributors for the total internal life cycle costs. The EoL treatment is a revenue source in all systems because it generates energy (in the case of the composite incineration) or materials (in the case of metal recycling). The composite and aluminium lighting columns present similar "cradle-to-grave" life cycle total cost. However, until the dismantlement phase, the aluminium column presents the highest environmental impact, whereas in the EoL treatment phase this scenario is reversed. The "cradle-to-grave" life cycle potential total cost and the environmental impact (*fossil fuels*) indicator of the steel lighting column are higher than those of the other columns.
Conclusions Even though the uncertainties in the LCC are larger if external costs are included, their consideration when modelling the economic performance of engineering products increases the probability of developing a more sustainable solution from a societal perspective.

Keywords Composite materials · Environmental costs · Externalities · Life cycle assessment · Life cycle costing · Lighting columns · Metals · Societal costs

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1 Introduction

Over the last years, many companies became aware of the vital importance of life cycle assessment (LCA) studies (Ribeiro et al. 2008; Peças et al. 2009; Alves et al. 2009). LCA studies allow understanding all relevant processes and environmental impacts involved in the life cycle (LC) of

products from the moment their raw materials are extracted from nature until the end of their service life, when they return to it. However, in order to fully assess the sustainability of those products, LCA should be complemented by economic and societal analyses (Klöpffer 2003, 2008). Life cycle costing (LCC) is the equivalent of LCA for economic assessment (Rebitzer and Hunkeler 2003; Hunkeler and Rebitzer 2003). Social life cycle assessment (SLCA) is the third pillar in the evaluation of sustainability. Although SLCA is considered to be still in its beginning, the idea is not new (Hunkeler 2006). The decision to evaluate all or part of the sustainability pillars depends on the objective of the study. In any case, if real money flows are a key issue, the inclusion of a LCC is advisable (Klöpffer and Ciroth 2011). LCC is a means to show that, by reducing use, maintenance or disposal costs, a financial compensation can ensue. With LCC different actors' perspectives may come to play. For instance, from the perspective of a manufacturer of a product made of a new material, it can indicate the maximum cost that would still make it competitive with a conventional one. From a customers' perspective, a LCC study is important because environmentally preferable products often have higher purchasing costs, while their full LC cost may be lower. The purchase price is only a small share of all the costs of a product during its LC, and the overall cost is therefore important for a purchase decision. Thus, motivation for the application of LCC comes from both customers and manufacturers.

LCA is a well-established and widespread, though still evolving, methodology and the only internationally standardized environmental assessment method (ISO 14040 2006; ISO 14044 2006). Over the past years, different LCA methodologies were developed and extensively demonstrated (Finnveden et al. 2009; Ferrão 2009). LCC, on the other hand, cannot be considered a uniform concept or framework. Until now, there is yet no international standard assessment method generally accepted, although an international code of practice was recently published (Swarr et al. 2011). There are many approaches, differing in goal, scope and methodology (Hochschorner and Noring 2011). According to the SETAC Working group on LCC, there are three different types of LCC (Ciroth et al. 2008): conventional, environmental and societal. Conventional LCC, to a large extent the historic and current practice in many governments and firms, is based on a purely economic evaluation. It considers the costs associated with a product that are born directly by a given actor but often neglects external costs. Environmental LCC summarizes all costs associated to a product LC that are directly covered by one, or more, of the actors involved in its LC (supplier, producer, user or costumer and/or final disposer). It includes the externalities that are anticipated to be internalized in the decision-relevant future. Societal LCC uses an expanded macro-economic system and incorporates a larger set of costs. It also involves, as opposed to conventional and environmental LCC, governments and other public bodies that could be indirectly affected through externalities. Societal LCC includes all of environmental LCC plus additional assessment of external costs, usually in monetary terms. One key argument for including external costs is the "polluter-payer" principle, accepted in the Organisation for Economic Cooperation and Development countries.

Externalities are, generally, defined as value changes caused by a business transaction that are not included in the price or are side effects of the economic activity (Ciroth et al. 2008). Monetary valuation of external costs (environmental and social costs) is a highly complex issue. As with internal (conventional) costs, externalities first have to be measured, quantified and related to the study reference (the functional unit of the system). Several approaches and methodologies have been applied (Ciroth et al. 2008; Viscusi 1993; Aravossis and Karydis 2004; Bickel and Friedrich 2005). Willingness to pay (WTP) and willingness to accept (WTA) are two well-known monetization approaches. WTP is the maximum sum of money a person is willing to pay to avoid something (e.g. emissions). WTA is the minimum amount a person is willing to receive to accept something undesirable. The most used quantification methods when there is no direct market are the contingent valuation method and the citizen value assessment. The former elicits a quantitative value measure, while the latter is a qualitative assessment. There is also the possibility of quantifying damage costs or prevention costs based on related market values. Damage costs relate to costs (in many instances losses in profits) due to some alteration, such as climate change due to CO_2 (greenhouse gas) emissions. Prevention costs relate to costs due to preventing a change, such as preventing CO_2 emissions via increased operational efficiency. When identifying and characterizing externalities, it is not always clear what to include or what system to use. Different contexts may favour different valuations of externalities. A key issue for an externality to be considered is that it can be detected and an actual market exists for it (Swarr et al. 2011). Economists have developed tools for estimation of externalities such as the concept of value of statistical life (VSL), using evidence on market choices that involve implicit trade-offs between risk and money (Viscusi et al. 1987; Viscusi 1993; Meyer et al. 1995; Viscusi and Aldy 2003). Notwithstanding the wide use of these tools, there is still concern over the uncertainties related to externalities estimates. However, although the incorporation of external costs brings uncertainties into a LCC study, the ensuing results can still be used as guidelines in product development. The main advantage of integrating externalities in LCC and evaluating all potential dimensions of a given product is the possibility of unifying the measurement unit, thus facilitating the choice between alternative product specifications.

Standard LCA methods have already been integrated with LCC methods to different extents. Rebitzer et al. (2003) expanded the traditional LCC method by incorporating LCA analysis results, namely the life cycle inventory (LCI) stage. This allows the flows of materials and energy to be quantified and provides a more complete vision of the system under study. Bovea and Vidal (2004) proposed a model that combines LCA, LCC, and contingent valuation. In this way, it is possible to identify alternatives that reduce simultaneously environmental impact and external costs, while maximizing product value. Rüdenauer et al. (2005) calculated separately the environmental burden and the costs and then used two-dimensional plots to show the effectiveness of different solutions as a support for decision making. Similarly, Kicherer et al. (2007) used also two-dimensional plots, but first normalized the results of the environmental and cost assessments with an external reference (inhabitant equivalent and gross domestic product, respectively). Kara et al. (2007) calculated individual indicators for the environmental performance and the associated social costs, for each stage of the product LC. Keoleian et al. (2006) proposed a framework that included both LCA and LCC, the latter integrating social costs. More recently, Huo and Saito (2009) proposed a single sustainability index that takes into consideration technical, economic and environmental features and employed it in a comparative analysis of different production systems. Several authors stress the importance of accounting for the external costs (environmental and social) of the full LC (Ciroth et al. 2008), although most studies normally do not consider them (Castella et al. 2009; Alonso et al. 2006). Ciroth et al. (2008) compiled and analysed the results of seven LCC studies from several activity sectors (from manufacturing to service). In this compilation, conventional LCC was found to be the most used practice (four cases), only one study being a societal LCC. Practice appears to be the driver of a specific practitioner LCC model. The costs considered differ between models, and therefore, the results from different studies are not comparable. Various studies have identified the difficulties of integrating LCC and environmental accounting, namely oversimplification to a monetary unit, lack of reliable data, complexity of the processes and conceptual confusion (Cole and Sterner 2000; Ciroth 2009).

The generalization of the use of polymer-based composite materials, which allow substantial weight reductions while maintaining mechanical performance, has brought interesting challenges for environmental scientists. Due to lightweighting, the automotive industry easily perceived composite structures as the best choice (environmental and economical), considering the overall LC of a vehicle (Castella et al. 2009; Roes et al. 2007; Song et al. 2009). This is not the case of the construction industry, where energy savings in the use phase due to weight reduction are normally not possible. However, other relative advantages may be considered, such as fast installation, high durability, high corrosion and fatigue resistance, and higher live load capacity. Thus, further insights into the full LC of this type of products (composites for stationary applications) may be of significant interest. In particular, the simultaneous consideration of environmental and economic aspects may draw light on their relative advantages when compared with identical products made with traditional materials.

In this work, a composite lighting column (CLC) for roadway use was chosen as case study and benchmarked with alternative lighting columns made with conventional materials: steel (SLC) and aluminium (ALC). In a previous work, the authors have already done a comparative LCA study of these lighting columns (Simões et al. 2012). The present paper describes the integration of the LCA and LCC methodologies, with inclusion of externalities (environmental and societal costs), applied to the same lighting column systems. To the best of the authors' knowledge, this is the first time such a comparative study of this type of products is performed.

2 Methodology

The LCA/LCC integrated framework adopted was derived from the analysis of the existing LCA and LCC methodologies. The LCA/LCC model consists in a parallel assessment, using the LCA methodology according to the ISO 14040 series (ISO 14040 2006; ISO 14044 2006) and the LCC methodology based on the Ciroth et al. (2008) guidelines. Methodologically, LCC, similarly to LCA, is divided into four stages, which are interrelated: goal and scope definition, cost and revenue inventory analysis, cost assessment and interpretation. This LCA/LCC model consists in implementing the LCA methodology to the product system and, in parallel, incorporating its results into the LCC study, namely in the LCI and life cycle impact assessment (LCIA) stages. This allows the flows of materials, energy and emissions (e.g. CO_2 eq., SO_2, NO_x, particles etc.) to be directly quantified. In the LCC and in the complementary LCA, there should be no double counting of externalities or environmental impacts. The goal and scope of the LCC can be seen as parallel and consistent with the goal and scope of the LCA (ISO 14040 2006; ISO 14044 2006). Key issues include the use of the same system boundaries and functional units (Rebitzer and Hunkeler 2003). However, to perform the LCC, it is also necessary to define the perspective, time reference, discount rate and to select the economic aspects and type of LCC that will be executed. In the life cycle cost and revenue inventory (LCCRI) analysis stage, cost data for each LC phase are collected, according to the goal and scope definition, accounting for the internal and

external costs. During this phase, LCI and LCIA data from the LCA study are used in order to quantify input and output flows. Life cycle cost assessment (LCCA) consists of the aggregation of cost data. There is no need to characterize, normalize or weight the inventory data, since they refer to a single unit (monetary currency). The LCCA results should be reported by economic aspects and not only by an aggregated total cost value, in order to ensure transparency in the LCC study. The interpretation phase procedures are similar to those of an LCA study. Ultimately, the LCA/LCC integrated results are "portfolio presentations" of the LC cost, combined with the key environmental LC impacts.

3 Life cycle costing

Lighting columns can be manufactured in several materials, but each solution must comply fully with the requirements of EN 40 series (EN 40-2 2004). Key properties that determine materials selection are the highest possible tensile, flexural and compressive strengths. Column survival to severe wind loading conditions is important, but breakaway performance is probably the most stringent specification. A study on the effects of road lighting on Dutch roads during darkness showed that it can reduce injury accidents by 50 % (Wanvik 2009a). However, collisions with lighting columns are also the cause of a large number of injury accidents on lit roads, reducing that safety effect (Wanvik 2009b). In Europe, the EN 12767 standard (EN 12767 2007) that deals with passive safety of support structures for road equipment classifies their energy absorption level in terms of impact and exit speeds. In short, passive safety is described by means of specific values obtained in full-scale crash tests. Composite lighting columns usually score well in passive safety tests (Lightweight Structures B.V. 2008). Many impact tests have shown that these resilient and tough columns increase traffic safety, mainly because they do not fall upon the vehicles in possible collisions. Therefore, one of the most important advantages of the composite lighting column solution is its safety. In the UK, lighting columns, followed by trees, are the most struck objects in urban areas (Passive Safety UK 2010). In that country, there are around 100 deaths and 3,000 injuries involving vehicles colliding with steel or concrete lighting columns and signposts each year (EPL 2010). Over 400 composite lighting columns have been installed, on a trial basis, across the UK. To date, only four major high-speed accidents involving these composite columns, resulting in no deaths, have been reported (National Composite Network 2010). However, other relative advantages may be considered regarding these columns, such as high durability, high corrosion resistance (even under extreme environmental conditions, e.g. salty sea air), no need of maintenance, fast and easy installation and no electric conductivity (lightning protection) (Europoles GmbH & Co. KG 2010). In the present LCC study, all these aspects are considered for the three lighting column systems referred to above.

3.1 Goal and scope definition

The LCC methodology was used to identify and compare all cost drivers associated with the LC of the three lighting column systems. The overall goal of the LCC study, built upon the previous LCA study results (Simões et al. 2012), is to identify economic and environmental win-win situations and trade-offs related to their LC. Therefore, the systems boundaries, functional unit and other relevant assumptions were the same as in that study. Lighting columns are structures used to illuminate the roadway during darkness or inclement weather (National Composite Network 2010). The luminaire, wiring and energy used were excluded from the study because they are equal for the three column systems. The functional unit considered as the base for assessment is a lighting column for roadway illumination that meets the requirements of EN 40 series (EN 40-2 2004), with 8 m height and a lifespan of 30 years. The LCC of all systems is based in a full LC perspective (producer perspective plus implications for market success, due to use and disposal costs). This perspective considers the raw materials production, column manufacture, on-site installation, use and maintenance, dismantlement and end-of-life (EoL) treatment and all intermediate transport processes (Table 1). The EoL treatment of the CLC is incineration with energy recovery, since its constitutive material (a thermoset composite) is not directly recyclable to a new product. On the other hand, SLC and ALC are sent to recycling facilities, as post-use galvanized steel and aluminium are relatively easy to collect and transform in existing process streams. An important difference between systems is that both the SLC and ALC need maintenance after 20 years of use due to metal corrosion, whereas the CLC needs no maintenance. Therefore, the latter releases no emissions into the environment during the use stage. The cost bearer "producer" is the company that manufactures the lighting columns. Ultimately, the final "user" of the lighting columns is the general population that circulates in roads and highways. The "user" also includes the construction and maintenance company that acquires the lighting columns from the manufacturer, installs them and is responsible for their conservation. Therefore, in this study, we consider two "users", the population that uses the roads and highways and the owner of the lighting columns. The "EoL" actor is the waste manager operator. The LCC reference year is 2010 and 3.5 % is the discount rate used (Great Britain Treasury 2003). The selected LCC type is the Societal LCC (Ciroth et al. 2008) that considers internal and external costs.

Table 1 Characterization of the lighting columns

Properties	CLC	SLC	ALC
Material	Polyester + E-glass fibre + pigment	Steel + zinc	Mix of primary and secondary aluminium
Production technology	Vacuum infusion	Cold rolling + hot-dip galvanization	Extrusion
Surface	–	Zinc coating	Sanded
Lifespan	30 years[a]	30 years	30 years
Maintenance	–	20 years	20 years
EoL	Incineration	Recycling	Recycling
Height aboveground	8 m	8 m	8 m
Total weight	60 kg	109 kg	37 kg

[a]To compare lighting columns, the CLC lifespan was considered equal to those of the metal ones (30 years). In fact, the expected CLC lifespan is higher (60 years) (Lightweight Structures B.V. 2010)

3.2 Life cycle cost and revenue inventory analysis

All economic aspects to be considered in this study were identified and quantified, taking in consideration that a Societal LCC accounts for all conventional costs plus the environmental and societal costs. Table 2 illustrates the economic aspects included in this study. Conventional costs refer to all the internal costs and revenues within the LC economic system. Therefore, all direct (straightforward costs, such as materials, labour, utilities etc.) and indirect (less tangible costs, such as training, employee safety etc.) costs along the LC of the lighting columns were considered. Since Environmental LCC includes externalities that are anticipated to be internalized in the decision-relevant future, costs of CO_2 eq emissions were accounted as an environmental LCC issue. Carbon prices are currently obtainable via a well-established European Union (EU) market. The EU Emission Trading Scheme (EU ETS) is the largest multinational, greenhouse gas emissions trading scheme in the world. At present, not all types of industries have to pay CO_2 emission impacts. However, in a near future, these impacts may result in costs for all companies, since they are one of the ways countries can use to meet their obligations under the Kyoto Protocol. Markets for other pollutants tend to be smaller and more localized. For instance, in the USA, there is a national market that deals in acid rain and several regional markets that deal in nitrogen oxides. Air pollutants were identified as a cause of aggravated respiratory and cardiovascular diseases that can lead to premature mortality (Friedrich et al. 2001). Direct health impacts due to fine particles (including <2.5 μm) were recognized as prime culprits. SO_2 may also have significant direct health effects, while evidence of direct health impacts of NO_x is less convincing. Although these impacts are usually not reflected in the price of goods, they should be considered when making decisions, since they imply a cost to society. As in Europe there is no market transaction for SO_2, NO_x and fine particles emissions, their damage costs were accounted as societal LCC issues. The safety features of the lighting columns also have a direct effect in the well-being of individuals that circulate in lit roads and highways (Wanvik 2009b). Therefore, they should be considered as a cost or revenue for society. Again, as there is also no market transaction for safety features, the damage costs/revenues of reduced mortality risk were similarly accounted as societal issues in this study.

Table 2 The three types of LCC considered and respective economic aspects

Types of life cycle costing	Input cost data	
Conventional	R&D	Use
	Market research	Maintenance and repair
	Development cost	Liability
	Production	Infrastructure
	Materials	Transport
	Energy	Storage
	Machines, plants	Materials
	Labour	Energy
	Waste management	End-of-life treatment
	Emissions controls	Waste collection
	Transports	Disassembly
	Marketing activities	Incineration, recycling or disposal
Environmental	Emissions—CO_2 eq	
Societal	Emissions—SO_2	
	Emissions—NO_x	
	Emissions—particles <2.5 μm	
	Safety features of the product	

The LCCRI done in this study includes LCI and LCIA results from the previous LCA study (Simões et al. 2012) and additional financial information. Budget and market costs were used for conventional costs of all LC stages. Data were derived from databases, bibliographic sources and collected via questionnaires sent to suppliers, product manufactures, users and EoL actors. The collected data

Table 3 Quantification of the emissions and the safety features of the three systems

External economic aspects	CLC	SLC	ALC
Emissions—CO_2 eq (kg)	189	101	35
Emissions—SO_2 (kg)	0.312	0.086	1.098
Emissions—NO_x (kg)	0.612	0.974	0.701
Emissions—Particles <2.5 μm (kg)	0.014	0.005	0.137
Product safety features (fatalities/ lighting column.year)	0	4.44E-06	0

were, when necessary, adjusted by price level, purchasing power parity and discount rates, to express all values in Euros 2010 (in the Netherlands). When this was not possible, an estimated average for the EU was used instead. All collected information constituted a database that allowed quantifying cost flows from every phase of the three column systems. Their emissions, modelled in the previous study (Simões et al. 2012), were quantified for all LC stages (Table 3).

In Table 3, the quantification of CO_2 eq emissions was performed using the Intergovernmental Panel on Climate Change characterisation model, while SO_2, NO_x and particles (<2.5 μm) emissions were quantified directly in the inventory. External costs of CO_2 eq were based in the carbon tax established by the EU ETS (Point Carbon 2011). Damage costs of SO_2, NO_x and particles (<2.5 μm) emissions were based on the ExternE project (Bickel and Friedrich 2005) as adapted by NETCEN (Watkiss and Holland 2000). The VSL monetizes the benefits of reduced mortality risk, capturing the value that individuals bearing the risk place on improved safety (WTP to reduce or avoid the risk) during the use stage. The risk to life reduction due to the increase of safety features of the CLC and ALC is based on the VSL for traffic accidents of Carlsson et al. (2010).

During the LCCRI, it was necessary to establish some assumptions. The Research & Development (R&D) phase was not included, as it was considered to be the same for the three alternatives. The costs of the lighting columns production (machines, plants, labour, emission control and marketing activities) were not available; therefore, they were estimated using general statistics from the Annual Survey of Manufactures of the US Census Bureau (2009). The number of fatalities per lighting column per year in the Netherlands was also not available; therefore, it was considered zero for the CLC, taking in consideration that there were no deaths in the UK road trial (National Composite Network 2010). For the SLC, this number was estimated using general statistics from the UK roads (Passive Safety UK 2010). For the ALC, it was also considered zero, allowing for the fact that aluminium absorbs more energy than steel (Aluminium Lighting Company 2011) and due to the lower ALC weight, compared to the SLC and even the CLC. One of the main risks in a collision with a lighting column is the falling of the column in the top of the vehicle. Since the ALC is lighter and more shock absorptive, it presents a smaller risk of death in a collision. Table 4 presents the best estimation of the internal and external costs, by LC stage, of the three lighting columns on a functional unit basis. The EoL treatment has a negative value, since it is a revenue source (benefit). Incineration with energy recovery costs includes the gate fee and operation costs that are compensated by revenues due to electricity sale. Metal recycling includes scrap and operation costs, also compensated by revenues due to secondary scrap metal sale. The CLC presents zero costs regarding the use and maintenance phase because this column does not need maintenance as its metal counterparts and is also considered the safest if a collision occurs.

3.3 Life cycle cost assessment and interpretation

Figure 1 presents the best estimation of the cumulative total costs, normalized on a yearly basis, of the three column systems on a functional unit basis. The systems depict a

Table 4 Internal and external costs of the three lighting column systems

Life cycle stage	Cost per lighting column life cycle stage (€)					
	Composite		Steel		Aluminium	
	IC	EC	IC	EC	IC	EC
Raw materials production	149.4	6.4	178.4	4.6	180.2	18.5
Lighting column production	178.0	0.03	114.1	1.4	118.1	2.1
On-site installation	24.2	0.3	36.2	0.5	23.9	0.3
Use and maintenance	0	0	31.6	244.0	31.6	2.2
Dismantlement	17.7	0.6	25.5	0.7	17.5	0.5
End-of-life treatment	−2.1	0.6	−7.4	−2.1	−5.7	−5.1
Total	367.2	8.1	378.5	249.0	365.6	18.3

IC internal cost, *EC* external cost

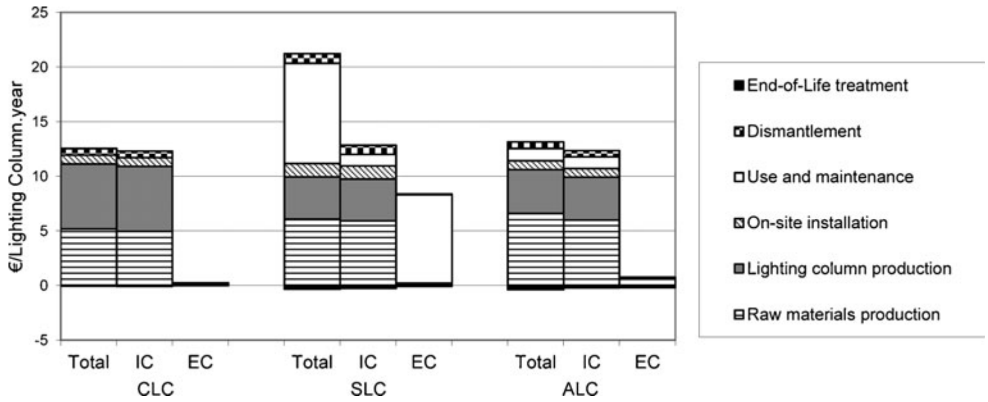

Fig. 1 Internal (*IC*), external (*EC*) and total costs of the three lighting column systems, normalized on a yearly basis

very similar potential internal LC cost, in spite of the higher costs of the CLC in the production phase (including the raw materials acquisition).

The internal costs of the use and maintenance stage of the metal lighting columns represent about 8 % of the total internal costs. The higher internal costs of the CLC in the production phase are compensated by the absence of maintenance in the use and maintenance stage. The SLC has higher potential external costs, 97 and 93 % above those of the CLC and ALC, respectively. The use and maintenance phase of the steel column is the main contributor for these costs. All lighting columns present small external costs related to emissions damage (CO_2 eq., SO_2, NO_x and particles), as shown in Fig. 2. Notwithstanding, the SLC has a very high cost associated to the safety features, since it presents a higher risk to life of individuals. The potential total costs of the SLC are the highest, almost 40 % above those of the CLC and ALC. The CLC and ALC potential external costs are less than 5 % of the internal costs, while for the SLC they are around 66 %.

The definition of the lighting column lifespan is an important factor in this study, since it determines the functional unit and therefore the reference to which all the input and output flows are normalized. The lifespan of the CLC is yet not known and was considered equal to that of the metal lighting columns in order to be possible to do a comparison. However, it should be noted that the lifespan of a lighting column depends on the construction material and local weather conditions (e.g. salty sea air). Therefore, based on manufacturers' experience, the SLC and ALC lifespans are estimated to be around 30 years, while for the CLC it is expected to be more than 60 years (Lightweight Structures B.V. 2010). Other important fact is that, statistically, the SLC and ALC need maintenance after 20 years of use, due to metal corrosion. It is also estimated that the economic depreciation of the three columns is done in a period of 20 years (Lightweight Structures B.V. 2010). The overall conclusion is that the lifespan of the SLC and ALC can be shortened, as the owner can chose to dismantle them after this period and install new ones, instead of doing maintenance. Thus, two alternative scenarios were analysed, where the lighting columns have different lifespans. The first scenario considers a lifespan of 60 years for the CLC and 30 years for both the SLC and ALC. As can be seen in Fig. 3, this scenario does not change the conclusions of the base scenario study, the SLC system showing again the highest potential total yearly costs, 70 and 39 % above those of the CLC and ALC, respectively. However, this scenario depicts a very different internal LC cost for the three systems. The CLC internal cost is 51 and 50 % lower than those of the SLC and ALC, respectively. The SLC presents again higher external costs regarding the use and maintenance phase, which contributes for its higher total cost. The cumulative total costs of the CLC are lower than those of the other columns, due to its longer lifespan that avoids consumption of new raw materials and energy, decreasing the

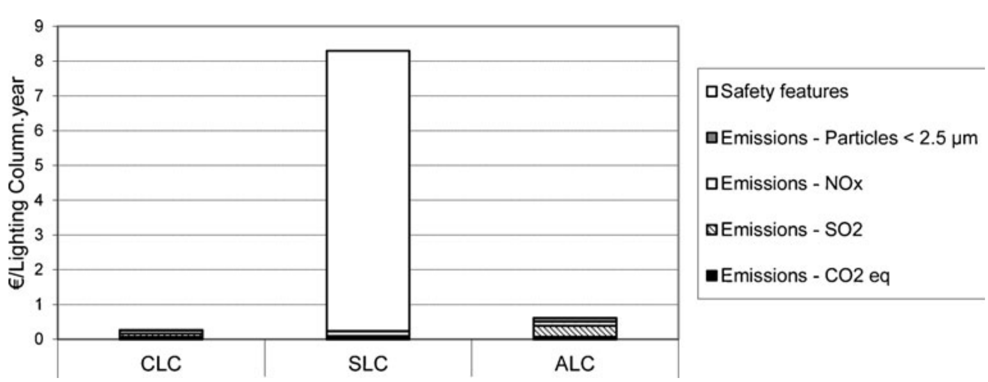

Fig. 2 External costs from emissions and safety features of the three lighting column systems, normalized on a yearly basis

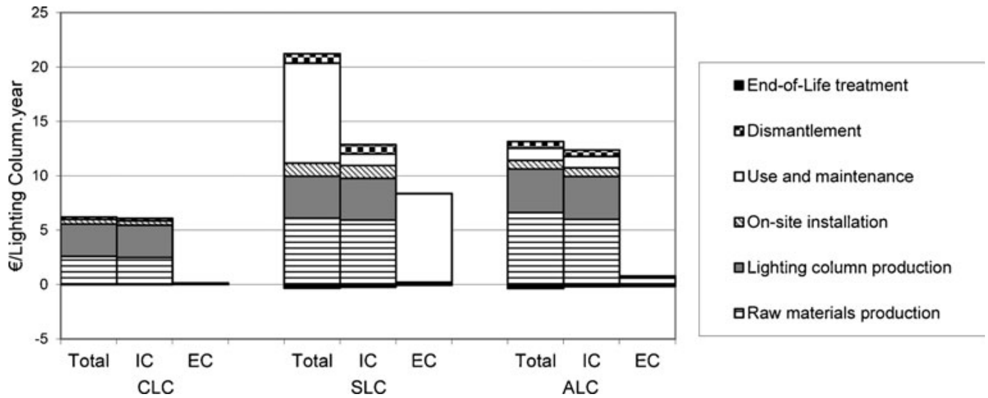

Fig. 3 Internal (*IC*), external (*EC*) and total costs of the three systems, in a CLC lifespan increased scenario, normalized on a yearly basis

corresponding acquisition and processing costs and the external costs due to emissions.

Another alternative scenario was analysed, in which lifespans of 30 years for the CLC and 20 years for both the SLC and ALC were considered. Again, as can be seen in Fig. 4, this scenario does not change the conclusions of the base scenario study. The SLC system shows the highest potential total costs, 53 and 34 % above those of the CLC and ALC, respectively.

As mentioned in the LCCRI, the ALC system considers zero fatalities per lighting column per year due to the characteristics of the material and the final product. However, this figure could be higher, although it will be always inferior to that of a collision with a SLC. Therefore, an alternative scenario was analysed, considering the worse possible ALC scenario, in which the number of fatalities per lighting column per year in a collision with an ALC was equal to that of the SLC system. As was to be expected, the results of this scenario are in harmony with the main conclusion of the base study. The ALC has a cost associated to the safety features as high as the SLC and the CLC system keeps presenting the lower potential total costs.

3.4 LCA/LCC integrated analysis

In a previous work, a LCA study (Simões et al. 2012) was performed to the three lighting columns using the Eco-Indicator 99 (EI99) LCIA method (Goedkoop and Spriensma 2001). The LCIA normalization results of the life cycle of the three lighting column systems are shown in Table 5 on a functional unit basis.

In order to perform an integrated environmental and cost analysis, the *fossil fuels* environmental impact category was selected as the key environmental impact indicator. The *fossil fuels* environmental impact category represents the extraction of a non-renewable resource expressed as the surplus energy needed for future extractions of fossil fuels. In fact, this indicator was identified during the previous LCA study (Simões et al. 2012) as one of the most significant burdens, in terms of scale of contribution, for all column systems. This impact category is also considered by the authors as being of great relevance for the plastic industry, as oil is the main source of the raw materials it uses, strongly affecting its availability and price (Simões et al. 2011). The cumulative total costs (internal costs plus external costs) for the "cradle-to-grave" LC of the three systems are analysed in combination with the *fossil fuels* environmental category in Fig. 5, on a functional unit basis.

In Fig. 5, each line is constituted by line segments that correspond to the different lighting columns LC stages, namely raw materials production, column production, on-site installation, use and maintenance, dismantlement and EoL. It can be concluded that the raw material production costs are very similar for all column systems, while the

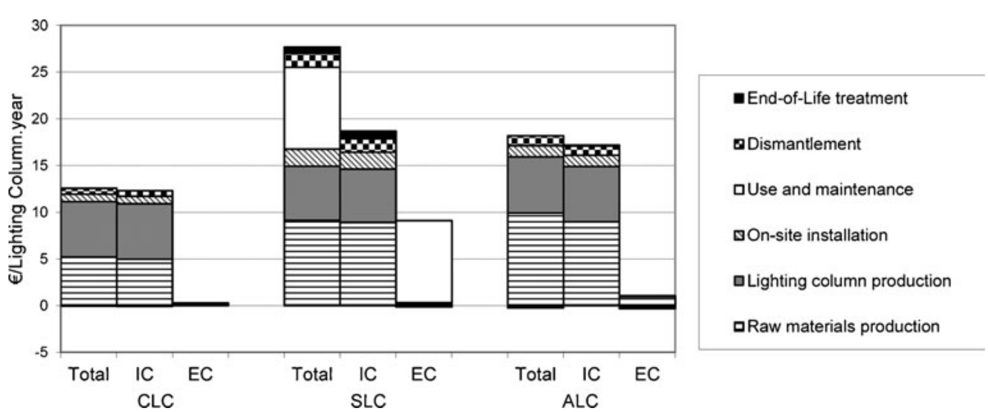

Fig. 4 Internal (*IC*), external (*EC*) and total costs of the three systems, in a SLC/ALC lifespan decreased scenario, normalized on a yearly basis

Table 5 LCIA normalization results of the three lighting column systems, using the EI99 method (environmental impact of the lighting column system/European person equivalent impact)

Impact categories	Characterization unit	CLC	SLC	ALC
Carcinogens	DALY	0.0073	0.0054	0.0168
Resp. organics	DALY	2.49E−05	7.98E−05	−9.01E−06
Resp. inorganics	DALY	0.0114	0.0269	0.0179
Climate change	DALY	0.0045	0.0024	0.0006
Radiation	DALY	6.13E−05	0.0001	0.0002
Ozone layer	DALY	1.81E−06	1.76E−05	−1.25E−05
Ecotoxicity	PAF.m^2 year	0.0006	0.0066	0.0015
Acidification/ eutrophication	PDF.m^2 year	0.0007	0.0022	0.0006
Land use	PDF.m^2 year	0.0001	0.0005	0.0006
Minerals	MJ surplus	0.0005	5.96E−05	0.0017
Fossil fuels	MJ surplus	0.0233	0.0265	0.0129

DALY disability adjusted life years (years of disabled living or years of life lost due to the impacts), *PAF* potentially affected fraction (animals affected by the impacts), *PDF* potentially disappeared fraction (plant species that disappear as result of the impacts), *MJ surplus* surplus energy (MJ) (extra energy that future generations must use to extract scarce resources)

environmental impact (*fossil fuels*) of this phase is quite high for the ALC. This high impact is due to the energy intensive process that is used in the production of aluminium. The CLC and ALC present similar "cradle-to-grave" LC total costs. Until the dismantlement phase, the ALC presents the highest environmental impact (*fossil fuels*), but in the EoL treatment phase this situation is reversed. This is due to the avoided materials consumption and emissions resulting from the recycling of the aluminium, making the ALC the column with the lowest environmental impact (*fossil fuels*). The "cradle-to-grave" LC potential total cost and environmental impact (*fossil fuels*) of the SLC are higher than those of the other columns, the use and maintenance phase being significant contributors for this result. The situation persists, even including the revenues and avoided emissions in the EoL phase (metal recycling).

4 Conclusions

Even though LCA studies allow understanding all relevant processes and environmental impacts involved in the LC of products, in order to fully assess their sustainability, those studies should be complemented by economic and societal analyses. The present work allowed a further insight into the full LC costs (internal and external) and environmental performance of three different lighting columns, making evident the win-win situations and trade-offs involved.

The total costs (internal plus external costs) of the "cradle-to-grave" LC demonstrated that the steel column performs globally worse than those made in composite or aluminium. Although the three systems present very similar internal costs, the SLC has higher external costs in the use phase that contribute for its higher total cost. Since the SLC presents a higher risk to life of individuals, it has a very high cost related to the safety features. The raw material production and column production are the main contributors for the overall internal LC costs. The EoL treatment is a revenue source because it can provide energy (in the case of the composite incineration) or material (in the case of the metal recycling). The sensitivity analysis performed confirmed that the CLC is economically preferable, since it has a higher expected lifespan and therefore avoids consumption of new raw materials and energy.

The *fossil fuels* environmental impact category was selected as the environmental impact indicator to

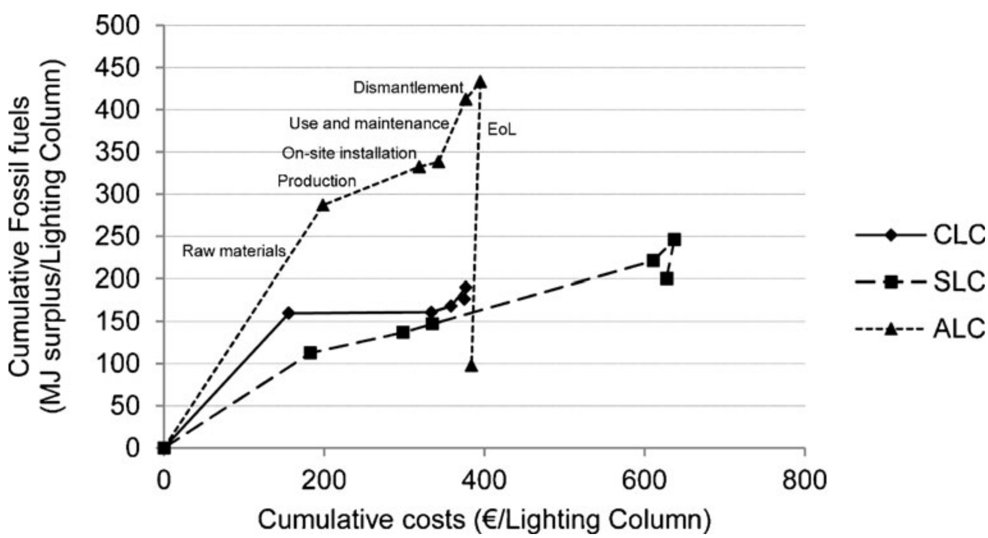

Fig. 5 Cumulative total costs versus fossil fuels impact category of the three lighting column systems

perform the integrated environmental and cost analysis. The CLC and ALC present a similar "cradle-to-grave" LC total cost. However, until the dismantlement phase, the ALC depicts a higher environmental impact (*fossil fuels*), while in the EoL treatment phase, this situation is reversed. This is due to the avoided materials consumption and emissions resulting from the recycling of the used aluminium, making the ALC the column with lowest environmental impact (*fossil fuels*). The "cradle-to-grave" LC potential total cost and environmental impact (*fossil fuels*) of the SLC are higher than those of the other columns, the use and maintenance phase being significant contributors to this result. The situation persists, even with the inclusion of revenues and avoided emissions in the EoL phase. Even though the uncertainties in the LCC are large when incorporating external costs (environmental and social), it is hoped that the present work was able to demonstrate that their consideration increases the probability of developing more sustainable products from a societal perspective.

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